Study of whispering-gallery-mode in a photonic crystal microcavity*

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The whispering-gallery-mode (WGM) photonic crystal microcavity can be potentially used for miniaturized photonic devices, such as thresholdless lasers. In this paper, we use plane wave expansion (PWE) method and study the WGM of H2 photonic crystal microcavities which are formed by removing seven center air holes in a photonic crystal. The WGM in these large-size cavities has some advantages compared with single defect WGM in the view of real device applications. We analyze the nearby air hole effect on WGM and conclude that WGM is more sensitive to moving towards the outside rather than moving towards the inside of a nearby air hole. In our case, if a nearby air hole is moved 0.1a away from the center, the WGM will disappear. If a nearby air hole is moved 0.6a towards the center, however, the WGM will still exit. We also analyze the structure with an air hole (r_m= 0.2a) in the center of the microcavity, and we find that the WGM is not affected by the central hole sensitively. As we increase r_m, the WGM remains unchanged until r_m is 0.64 times greater than period a. It is found that the tolerance of WGM to the displacement of nearby air holes and the occurance of central holes is large enough to fabricate electrical injection structure.

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Photonic crystal, a kind of artificial periodic dielectric structure[1,2], has attracted lots of attentions recent years. An important characteristic of this structure is the presence of photonic band gap (PBG). The electromagnetic wave propagation inside a photonic crystal is forbidden in all directions for a certain frequency range due to the PBG effect. It offers great possibilities of controlling the flow of photons and results in various applications such as lasers[3], light-emitting diodes[4,5], planar waveguides and photonic filter[6,7].

Whispering-Gallery-Mode (WGM) photonic crystal microcavity is a kind of photonic crystal application and can be potentially used for miniaturized photonic devices, such as thresholdless lasers[8]. Compared with square lattice structures, triangular lattice air hole array structures have a large photonic band gap for in-plane TE polarization. There are two main reasons for working on WGM in photonic crystal microcavity. First, the simple structure and uniform symmetry of this kind of microcavity benefit WGM sustaining very well. Second, both total internal reflection (TIR) effect and photonic band gap (PBG) effect are related to WGM. The high Q factor and large central node with zero field distribution of WGM are very promising and suitable for electrical injection structure used in microcavity lasers[9].

In this paper, we study the WGM of H2 cavities which are formed by removing seven air holes away from a regular photonic crystal. The WGM in these large-size cavities has

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some advantages over single defect WGMs in the view of real device applications. Through plane wave expansion (PWE) method, we analyze the effects of nearby and central holes on WGM in the microcavity by moving or introducing corresponding air holes in the microcavity.

Plane wave expansion (PWE) is widely used in photonic crystal researches[10]. The dispersion of the periodically arranged dielectric structure, also called band structure, can be obtained by this method. According to the band structures, many useful parameters could be extracted, such as PBG, phase velocity, energy velocity, mode and so on.

To derive the equations of the PWE method, we start from Maxwell's equations:

$$\nabla \cdot \boldsymbol{D} = 0 , \quad (1)$$

$$\nabla \cdot \boldsymbol{B} = 0 , \quad (2)$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} = -m\frac{\partial \boldsymbol{H}}{\partial t} , \quad (3)$$

$$\nabla \times \boldsymbol{H} = \frac{\partial \boldsymbol{D}}{\partial t} , \quad (4)$$

where $\boldsymbol{D}=e_0 e(r)\boldsymbol{E}$ and $\boldsymbol{B} = m_0\boldsymbol{H}$.
Taking time-independent solutions

$$\boldsymbol{E}(\boldsymbol{r},t) = \boldsymbol{E}(\boldsymbol{r})\mathrm{e}^{-\mathrm{i}wt} , \quad (5)$$

$$\boldsymbol{H}(\boldsymbol{r},t) = \boldsymbol{H}(\boldsymbol{r})\mathrm{e}^{-\mathrm{i}wt} , \quad (6)$$

the Helmholtz equation is

$$\nabla \times (\frac{1}{e(\boldsymbol{r})}\nabla \times \boldsymbol{H}(\boldsymbol{r})) = \frac{w^2 m(\boldsymbol{r})}{c^2}\boldsymbol{H}(\boldsymbol{r}) . \quad (7)$$

The Block's theorm is used

$$\boldsymbol{H}(\boldsymbol{r}) = m(\boldsymbol{r})\mathrm{e}^{\mathrm{i}(\boldsymbol{k}\cdot\boldsymbol{r})} , \quad (8)$$

where $m(\boldsymbol{r})$ is a function with the periodicity of the lattice, and we obtain

$$\hat{L}m_k = (\mathrm{i}k+\nabla)\times(\frac{1}{e(\boldsymbol{r})}(\mathrm{i}k+\nabla))\times m_k = v m_k , \quad (9)$$

where v is the normalized frequency, and $\hat{L}$ is an operator we define. Eq.(9) is the fundamental equation that will be solved by plane wave expansion. v is eigenvalue, m_k is eigenvector, and k is a free parameter. By solving v in suitable path in the first brillouin zone, a band structure can be obtained.

In this section, we study the two dimensional air hole photonic crystal with triangular lattice. The refractive index of the slab material is chosen to be 3.4, the air hole radius r is 0.36a, and a is the periodicity of the triangular lattice. The microcavity, which is called H2 cavities, is formed by removing seven air holes in the periodic triangular lattice, as presented in Fig.1.

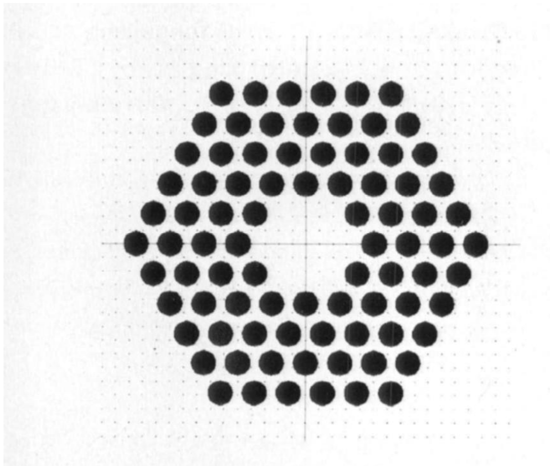

Fig.1 H2 photonic crystal microcavity

The electromagnetic fi eld distribution in the microcavity can be gained by the PWE method. For a structure with a defect, we need to define a supercell so that the calculation domain is much larger than a single unit cell of photonic crystal. We choose the 6×6 unit cell as the supercell. And the numerical domain does not even show the same shape as the wholly physical structure. In our case the supercell is diamond-like as shown in Fig.2.

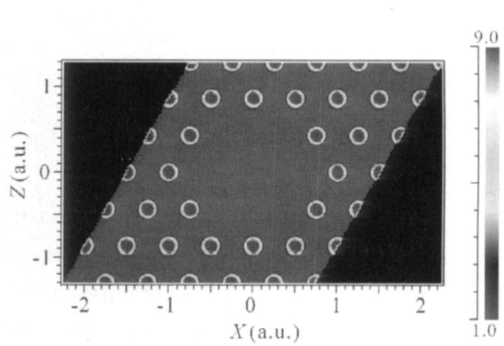

Fig.2 Diamond-like supercell

As shown in Fig.3, a typical WGM mode exits in the microcavity. The mode exhibits a standing wave pattern along the cavity boundary and there is no electromagnetic energy in the center. In the WGM of triangular lattice photonic crystal cavities, the number of high-intensity lobes is equal to that of neighboring holes around the cavity, so that the WGM in the H2 cavity has 6 high-intensity lobes.

Then we calculate the photonic band gap, shown in Fig.4. The first Brillouin zone and K-path are also shown in Fig.4. The band gap is between 0.51a/l and 0.52a/l.

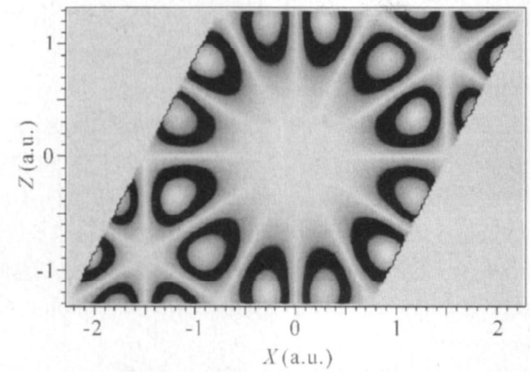

Fig.3 WGM mode in the H2 photonic crystal microcavity

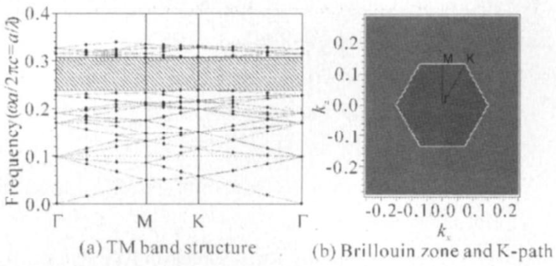

Fig.4 TM-polarization photonic band gap and the first Brillouin zone of this structure

First, we move one of the nearby air holes outward for 0.1*a*, shown in Fig.5.

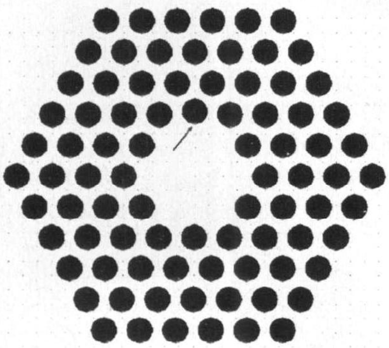

Fig.5 Outward movement of a nearby air hole for 0.1*a*

Then we simulate this structure mode. The WGM disappears, although we only move out the nearby air hole slightly. In other word, the WGM is very sensitive to nearby air holes' outward movement.

In the other case, we move one of the nearby air holes towards the cavity center, as shown in Fig.7. Until the nearby air hole moves towards the cavity center more than 0.6*a*, the WGM doesn't exit. Therefore, the WGM is not sensitive to the nearby air hole moving towards the cavity center.

We add a hole, whose radius is r_m=0.2*a*, in the center of microcavity, as shown in Fig.9. We also simulate the electro-

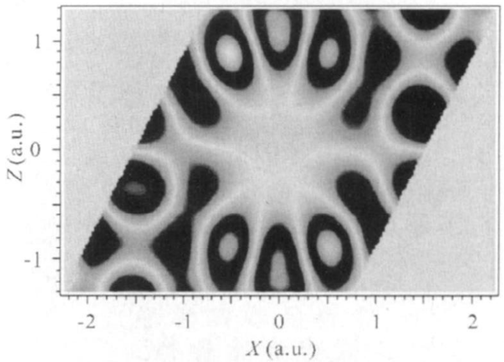

Fig.6 WGM disappearance

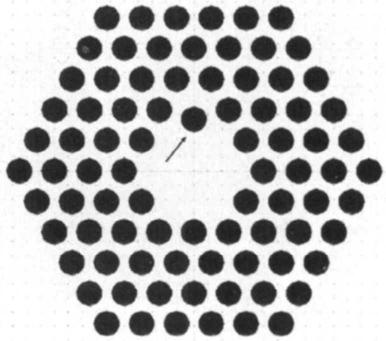

Fig.7 Movement of a nearby air hole towards center for 0.3*a*

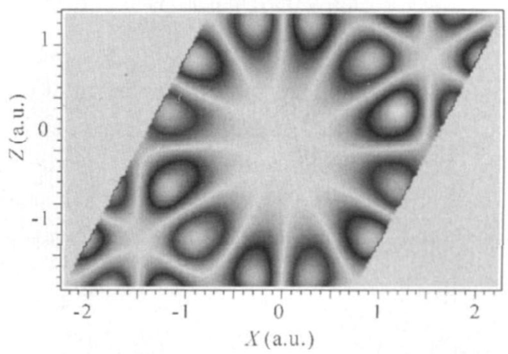

Fig.8 WMG in the cavity with one nearby air hole moving towards center

magnetic field distribution in the microcavity. As shown in Fig.5, we get almost the same results as shown in Fig.3. This suggests that the WGM in the microcavity is unsensitive to the central hole or defect. This is consistent with the property of WMG that there is no electromagnetic energy in the center.

However, when the center hole radius r_m increases to 0.64*a*, the electromagnetic field distribution illustrated in Fig.10 suggests that the central hole and the region of WGM overlap, which disturbs the electromagnetic field, resulting in the disappearance of WMG.

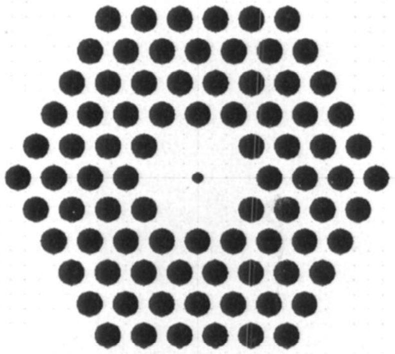

Fig.9 Photonic crystal microcavity with a central hole, $r_m = 0.2a$

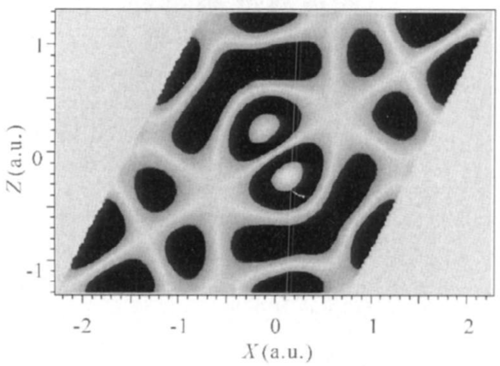

Fig.10 WGM disappearance with central hole radius of 0.64*a*

In this paper we simulate and analyze WGM of photonic crystal microcavity. First, we analyze the nearby air hole effect on WGM. The WGM is sensitive to moving out a nearby air hole but not moving it towards center. When a nearby air hole moves out 0.1*a*, the WGM disappears. However, even if the air hole moves to center for 0.6*a*, the WGM still exits. And then we analyze the structure with an air hole ($r_m = 0.2a$) in the center of the microcavity. We find that the WGM is not affected by the center hole at all. As we increase r_m, we obtain the same results. Until r_m is 0.64 times more than period *a*, the WGM disappears. The tolerance of WGM to hole's displacement and occurence is sufficient for pratical fabrication of injection structure. These results mean that WGM is advantageous to achieve electrically pumped photonic-crystal lasers.

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